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# Practical Application of CAE in the Design Process of the Floating Stages of the Lakeside Festival in Bregenz - Austria

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**Abstract**

The design of modern and architecturally complex constructions in civil engineering can only be effectively achieved through the application of Computer-Aided Engineering (CAE). This requires, on the one hand the use of fully 3D CAD Systems during the architectural design process and on the other hand the use of fully 3D numerical calculation methods like the Finite Element Method (FEM) during the engineering construction process. The combination of the aforementioned CAE methods allows for the development of highly sophisticated structures. The practical application of these methods will be revealed by examining the floating stages of the lake festival in Bregenz/Austria, these stages are designed and built anew every second year. The aim is to show the development process from the initial designs up to the finished stage; a process made possible thanks to a close collaboration between designers and engineers.

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*Keywords:* Floating stage, multidisciplinary engineering, steel construction, CAD, FEM;

## 1. Bregenz Festival

Here The Bregenz Festival is a cultural festival that attracts over 200,000 visitors every year. Its major attraction is the open-air operas which take place on the world's largest lakeside stage, located on the south-eastern bank of Lake Constance.

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In 1946, a year after the end of WWII, thanks to the organization of an occupying French officer and opera enthusiast or citizens of Bregenz, the first Bregenz Festival took place. Since at that time, the city of Bregenz did not have a theater, Mozart's Bastien et Bastienne was performed as an improvised and quick solution on two gravel barges on the lakeside [1]. One barge carried the stage set and the second carried the orchestra.

The Bregenz Festival has become an established institution of Austrian culture ever since. Year after year more and more visitors wish to be among the audience of the opera on the lake.

For this reason, in the season of 1985/1986 it was decided to vary the performances according to a biennial rhythm that would allow the construction of the increasingly complex stage sets. Presently the organizers invest EUR 6 million every second year in the construction of the new stage on lake Constance. These costs encompass the construction of a reduced stage set for indoor performances in the case of rain, as well as the dismantling, disposal and recycling after the final performance. The floating stage offers approximately 7 000 seats and their utilization to date has always between 90 - 99%. This leads to the deduction that up to 400 000 guests visit the opera performances on the floating stage over the two-year term [2].

Fig. 1. Mozart‘s Bastien et Bastienne (© Bregenzer Festspiele).

## 2. Planning Stages for a Stage Set

Each new stage set represents a challenge for the entire team who often have to find completely new solutions across varying engineering disciplines, whilst at the same time remaining within budget. This must all occur within a very strict schedule as the premiere cannot be postponed. As a result, the organizers of the Bregenz Festival assign the construction process and its execution to various engineering offices and executing companies. In order to do so, the complete stage set is divided into separate subprojects. This procedure makes it possible, in the case of a supplier failure, to still ensure the final delivery.

The planning of a stage set breaks down roughly into four stages: preliminary studies, model release, planning for the tender's submission, as well as the workshop and detailed planning.

The festival's artistic director decides which performance will take place. The artistic director is also responsible to designate a director and stage designer. These members of the team then present their proposals for the realization of the piece in the form of sketches and simple paper models. In the following brainstorming phase, members of the staff of the Bregenz Festival and external engineering offices examine the technical feasibility of the project as well as provide the initial cost estimations. At this point all the drafts can still be discarded or modified.

Usually the given budget-limit forces the stage designers to concentrate on the vital stage elements. Often enough, thanks to this process, far more expressive stage sets have come into being in the end.

When the model is released, the festival's senior management gives their seal of approval to the choice of director and to the planned stage set. Thus, a model for the stage set is built to a scale of 1:100. This model includes all parts of the stage set in such a degree of detail that, in addition to the form, even the artistic specifications are defined on the surfaces.

The contractors are then expected to perform the workshop and detailed planning unless they have already included this in the planning documents during the tender. As the Bregenz Festival wants a 'turnkey stage setting' in order to avoid interface problems, part of the suppliers' job is also to obtain the various approvals of a civil engineering character. Moreover, when constructing at the actual lakeside, the authorities require extra proof of all structural analyses according to different legal regulations [3] [4] and standards [5] [6].

## 3. Engineering Disciplines Involved

A number of seemingly conflicting requirements guide the design of this temporary stage which finds itself on water that reaches an approximate depth of 4 m. It must be a fantastical appearance and be up to 2-3 times larger than a typical stage in order not to be dwarfed by its natural surroundings, however it must also be as lightweight as possible as it is founded on steel and wood piles that extend into the lake bed and into a permanent concrete nucleus with a limited load capacity of only 10 kN/m². Once dismantled, the stage must be fully recyclable or reusable, but it must perform and withstand extremes of weather and temperature for two full years, including thunderstorms, gales of up to 135 km/h, snow loads of up to 2.1 kN/m² and temperatures that drop to -20 degrees Celsius. It is also important, to take into account the 2.3 m height fluctuation in the water level when designing the stage.

For these reasons the creation of such stage sets remains firmly in the 'steel construction' domain; it combines, in fact, precast and lightweight constructions with stiffness structures [7]. The open air stage sets in Bregenz are precise civil engineering works which have to withstand various extreme weather conditions. For the operating state the wind speed is limited to up to 60 km/h; during the out-of-operation period however, the wind and snow loads are to be considered according to the Eurocode standard [8]. As soon as the structural engineer has provided the data for the out-of-operation position, the city of Bregenz requires the stage scenery to be presented as impressively as possible, even beyond the Festival time, as many tourists visit the lake stage throughout the year. The available load reserves of steel constructions, determined through calculation, using an elastic-elastic method for the operating state and a plastic-plastic method for the out-of-operation position, are applied.

All the productions have movement mechanisms in order to change the sets during the performance without having to pause; therefore, these movements ought to occur in a smooth manner, appear easy and playful and be as silent as possible. These requirements can be fulfilled only by providing sufficient stiffness. The stage settings have to be mounted and dismantled in a relatively short time. The bigger parts of every new stage set are prefabricated in the steel constructor's workshop. The production's work can therefore already be initiated before the end of the previous playing season.

## 4. Particular Examples of Stage Settings

### *4.1. Un ballo in maschera (1999/2000)*

A milestone in the stage design in Bregenz was the stage for the opera *Un ballo in maschera*. For the first time, a complete 3D CAD model was established. Far superior to former times with the 1:100 models, the 3D-CAD model allowed the examination of lines of sight and the exact definition of the geometry. As a result, the 3D CAD model also became an obligatory tool for the stage designer. Even the light designers soon realized the advantages obtained by using a 3D model particularly in this situation, where no even surface was present.

A challenge for the engineers involved proved to be the construction of "Mister Hine" with a total height of 24.3 m, where the diameter of the skull alone was 7.1 m.


Fig. 2. Stage setting *Un ballo in maschera* – skeleton, (photo B. Hofmeister).

Whilst similar to a human skeleton, it can be noted that bones from the neck and of the backbone below the ribs are removed. The reason for this modification had been the geometric interpretation of the stage designer Richard Jones.

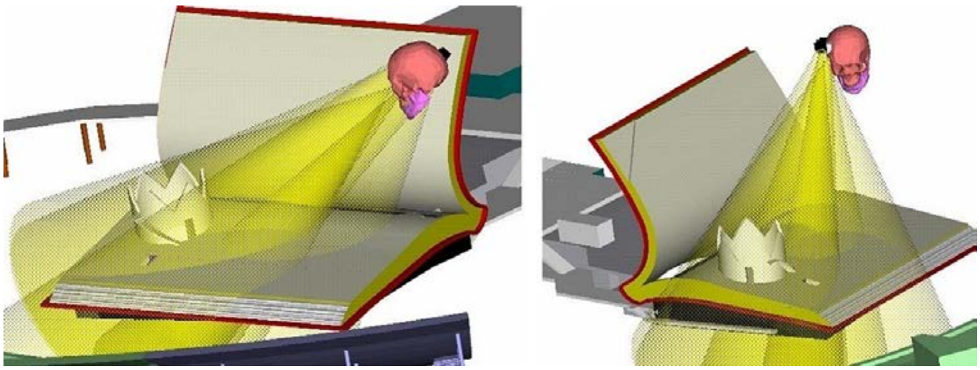

Fig. 3. Stage setting *Un ballo in maschera* – studies of light design.

### *4.2. Il Trovatore (2005/2006)*

In the case of the opera *Il Trovatore* the set designer Paul Steinberg and the director Robert Carsen created a spectacular refinery made of industrial components in a poison-like red colour which moved unmistakably into the present the characters' reckless striving for power, which is the focus of the whole opera.

The stage of *Il Trovatore* represents again a milestone when taking into account the design management. Before this point in time, only general drafts with pre-dimensions and rough material bills were prepared for the tender stage. The whole workshop design, including all detail drawings, had to be prepared by the construction companies. This was a reason why many construction companies would not bid: the risk was too high. For the stage of *Il Trovatore* a complete workshop planning was done prior to the tender. As a result, offers grew in number and in quality.

A main part of this stage setting was the pipeline bridge with a span of 21 m and 16 m height. Contrary to real pipeline bridges, the environmental loads were the dominant elements to consider for the construction. The live loads (persons on the access platforms) were nearly negligible for the dimensioning of the structure. Due to the lightweight design, stability and local buckling became important. We determined the so called 'post-critical loading capacity' of the shell structures. The structural analysis of this capacity was performed by using FEM for the complete structure. The occurring deformation and oscillations are very often significant for dimensioning. For deformation and oscillations at the floating stage the following rule is valid: it should match with what can be expected from trained actors (singers and stunts).

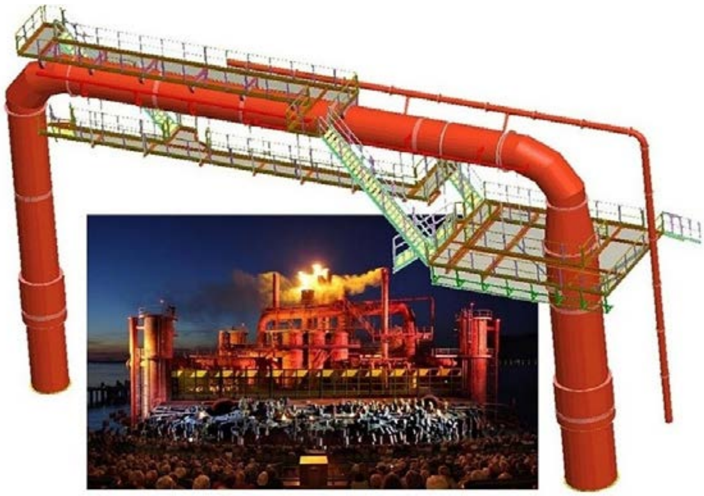

Fig. 4. Stage setting *Il Trovatore* and pipeline bridge model for the tender.

### *4.3. Tosca (2007/2008)*

So much attention as that which was given to the construction of the stage set for the *Tosca* had not been given to any other opera before. With certainty, the grandiose design of Johannes Leiacker played a part; a huge eye with a moving eyeball. On the other hand, to coincide with the soccer European championship and the film recordings for James Bond, the *ZDF* sport studio took every effort to ensure additional media presence.

The biggest challenge in the *Tosca* stage design was in providing the necessary strength to safely move the eye while respecting the weight limits of the foundation. The stage's moving parts weighed about 250 metric tons, while the entire stage and foundation weighs only 463 metric tons. Another important limitation was that each component had to be moved on to the stage by a crane that could handle only about 12 tons. The small bridge between the stage and the land is limited to a mere 1 ton per square meter. This means that in order to move any larger component, they had to be divided into smaller pieces and assembled on the stage itself.

Further challenges resulted from the components' materials: The eye and eyeball were made of a composite construction with a steel frame and a wooden outer surface. The composite construction increased the complexity of the analysis since connecting steel and wood together in a shear plane provides additional stiffness beyond the sum of the properties of the two materials. In addition to the classical application's fields of simulation technology represented by kinematic analysis on a 3D-CAD model and by dynamic FEM calculations, further simulation technics were used in the creation of the stage set of the *Tosca.* Beside the classical method for determining the wind forces according to EN 1991-1-4 [8], simulations of air flows were performed by using Computational Fluid Dynamics (CFD).

Fig. 5. Stage setting *Tosca* (© Bregenz Festival/Benno Hagleitner).

The result of such simulation is useful in that it achieves detailed information about local wind forces and air flows under normal thermal conditions, which in turn affects the acoustics. Improvements for the direction of hearing can be achieved by avoiding areas with relative high air flows and reducing the sound volume.

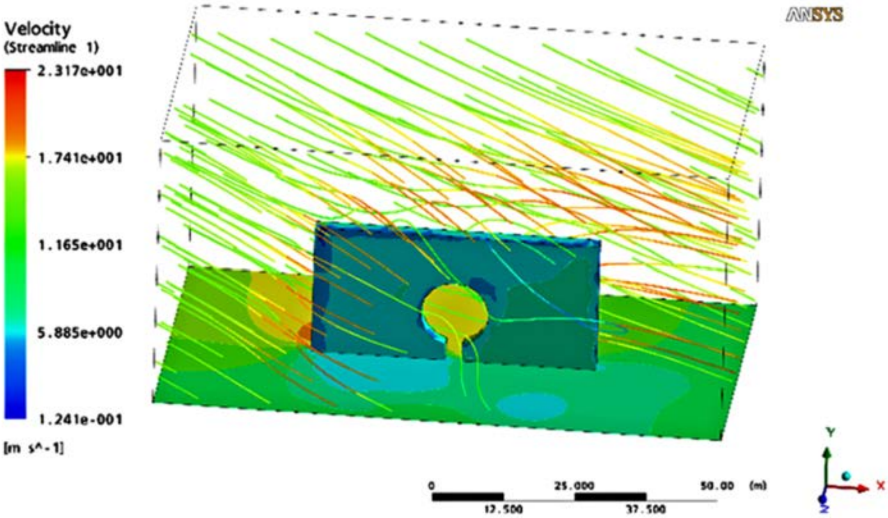


Fig. 6. Stage setting *Tosca* – CFD simulation of air flow.

### *4.4. The Magic Flute (2013/2014)*

The stage of The Magic Flute was dominated by three 27 m tall, steel sculptural elements fashioned into individual “dragon dogs” – known as Wisdom, Reason and Nature – which were connected at their top with footbridges. The stage itself was a 360-degree revolving dome with a diameter of 22 m founded upon 36 steel and wood piles that extended 6 m into the lake bed at its front and onto the permanent concrete core at its back. Taking it into consideration as a construction project, the dome represented a combination of a geometrically complex civil engineering structure with a large machine. The central column and round peripheral beam for the dome were fabricated with steel to simplify the construction and movement on the stage. This made standard constructive solutions possible when dealing with the interfaces of the machine components like the large-diameter antifriction slewing ring in the central column and of the wire drive used to convert the rotary motion on the round peripheral beam. The dome's rotation had to occur as quietly as possible because of the microphones mounted on the stage that amplified the music.

Fig. 7. The Magic Flute – CAD model (© Bregenz Festival/Simon Wimmer).

### *4.5. Turandot (2015/2016)*

The stage designers often have precise ideas of how the surfaces of the stage settings' elements have to look and provide models constructed to a scale of 1:100. These models have to be transformed into a precise CAD model in order to be able to recreate the same surfaces and the steel support structure underneath.

Fig. 8. Photo of stage setting model - scale 1:100 (© Bregenz Festival).

The classical data collection system performs measurements with calliper and ruler leading to the subsequent CAD modelling via manual data entry. This process is extremely time-consuming and often too no precise when dealing with complex sculptures. In the case of the model statue for the stage set of *Turandot*, the 1:100 statues were scanned with a high precision 3D laser. The scanned data was then converted into a CAD model. **Chyba! Nenašiel sa žiaden zdroj odkazov.** shows the laser scanner that was used and, as an example for the resulting 3D CAD model, a warrior of the terracotta army.

a) b)

Fig. 9. (a) Laser Scan System, (b) Converted CAD model.

## 5. Bregenz Open Acoustics

Even the most beautiful and most complex stage design can only account for one aspect of the performance. The most important part of an opera is naturally, the music. Engineers from the Bregenz Festival have developed their own system known as the BOA (Bregenz Open Acoustics) in cooperation with the Fraunhofer Institute [9].

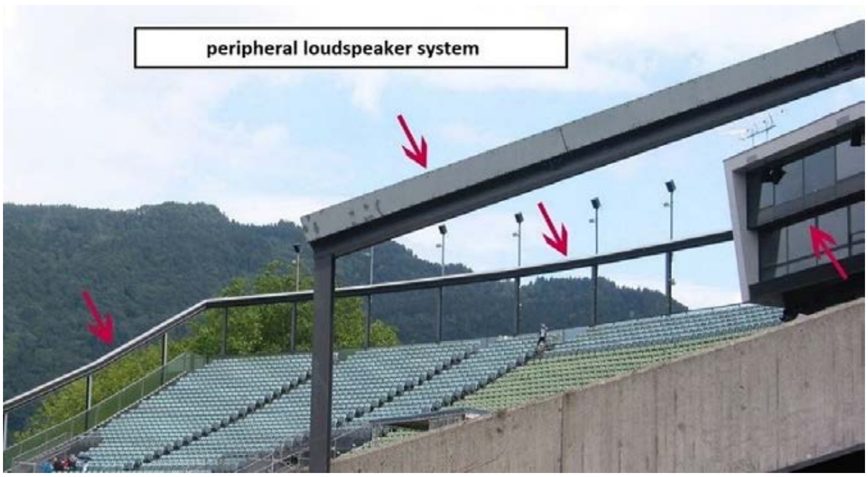


Fig. 10. Bregenz Open Acoustics (BOA).

This system creates a revolutionary sound experience for its audience. The result is a far superior sound than the one any typical surround system technology could produce. By means of wave field synthesis, the entire auditorium is immersed into a ‘cathedral of sound’. The BOA allows for a sensation of precise directional hearing accompanied with music of studio-like quality. BOA requires approximately 800 loudspeakers to be installed which surround the complete auditorium. Every loudspeaker needs its own independent control signals, which are different for each loudspeaker. Thanks to this award-winning acoustic system, the orchestra does not play on the stage anymore but in the festival hall. The music is transmitted via loudspeakers and the conductor's instructions can be followed on a screen in the open air arena.

## 6. Conclusions

Up to a few years ago, the director, the stage designer and specialized craftsmen were the only persons responsible for the creation of open-air stage settings for the Bregenz Festival. Nowadays, the construction of modern open-air stages is a multidisciplinary oeuvre.

In the early stages, before the definitive performance is fixed by the director, the completion of a 3D model, where every scene can be played one after the other like in a film, takes place as standard. At this point, significant changes of the whole production can still occur. Simultaneously, the costs for the stage set are kept under scrutiny.

Because of the numerous effects and movements, a stage set constitutes a static construction. A modern stage setting can also be compared most readily with a mechatronic system. Consequently, the planning of an open-air stage requires a close collaboration between stage designer, structural, mechanical and control engineers, computer scientist, light and acoustic designer, etc. in order to create a comprehensive simulation model. This simulation model does not, thus, undergo the limitations of a 3D geometry representation but comprises also the data for the structural engineers (FEM model), the mechanic systems and elements of the control systems. It serves, in the end, as basis for the implementation from the part of the executive companies (steel and wood companies, mechanical engineering companies as well as executors of the management and system control technology).

## Acknowledgements

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